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ESTIMATION OF MAXIMUM SURFACE CONCENTRATIONS FROM SOURCES NEAR COMPLEX TERRAIN IN NEUTRAL FLOW

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Abstract—A wind tunnel study was conducted to determine maximum ground-level concentrations for a variety of source positions (locations and heights) both upstream and downstream of two model hills, an axisymmetric hill (maximum slope 24°) and a two-dimensional ridge (maximum slope 16°), immersed in a simulated neutral atmospheric boundary layer. Terrain amplification factors derived from these measurements were used to construct contour plots showing regions or 'windows' of enhanced ground-level concentration. These windows of enhanced ground-level concentration are shown to be a useful guide for estimating the effects of complex terrain on pollutant dispersion or, conversely, for determining source locations near complex terrain which minimize the enhancement of ground-level concentration.

Key word index: Atmospheric diffusion, complex terrain, wind-tunnel modeling, air pollution, atmospheric boundary layer.

1. INTRODUCTION

The estimation of pollutant concentration from sources in flat or nearly-flat terrain has been dealt with extensively through the application of standard dispersion parameters to Gaussian plume models (Pasquill, 1961; Gifford, 1961; Turner, 1970; Hosker, 1974). For sources located in complex terrain, however, there are no established techniques for estimation of concentrations, owing primarily to the difficulty of describing the flow field near complex terrain and to the problems of parameterizing the many types of complex terrain which may be encountered. In recent years, several mathematical models have been developed to calculate dispersion in complex terrain. Most of these models are based on Gaussian plume assumptions with the balance being numerical-grid models. White *et al.* (1985) provide a brief assessment of the scientific merit and relative performance of eight of these models. The bulk of them require considerable development before being applied to regulatory practice. Additionally, the focus of the Environmental Protection Agency's model development effort (Holzworth, 1980) has been on simulating plume/terrain interactions (e.g. impaction from upwind sources) during stable rather than neutral flow. The problem of plume downwash in the wakes of terrain obstacles is generally relegated to physical modeling, but physical modeling of every potential source location is impractical. What is frequently needed is simply a qualitative description of how terrain may affect a plume released near a given terrain feature (i.e. will the plume go around or over the terrain?), supplemented by a

quantitative estimate of the enhancement of maximum ground-level concentration. Additionally, one would like to know what combination of source height and distance from the terrain feature is required to prevent 'excessive' ground-level concentrations from occurring. Such guidelines have been established for those cases where a structure in the immediate vicinity of the stack is responsible for inducing downwash (Snyder and Lawson, 1976; EPA, 1981; Lawson and Snyder, 1983), but similar criteria for determination of stack height and location in complex terrain have yet to be developed. This study examines one approach to establishing general guidelines for estimating the effects of sources located near terrain obstacles or, alternatively, for determining an appropriate stack height and location required to avoid excessive ground-level concentrations.

The effect of complex terrain on the transport and diffusion of pollutants from a nearby source is generally to increase ground-level concentrations (glcs). Considering a source upwind of a hill, the maximum glc is increased because the convergence of the streamlines brings the plume centerline closer to the hill surface and the increased turbulence effected by the hill diffuses larger concentrations to the surface (Hunt *et al.*, 1979; Snyder and Britter, 1987). For a downwind source, the maximum glc may be increased due to (a) streamlines descending toward the surface in combination with greatly enhanced turbulence and reduced transport speeds, and/or, if flow separation occurs, (b) the plume being recirculated within the cavity on the lee side or being transported directly to the surface (Castro and Snyder, 1982).

If the source is far enough upstream of the hill and the pollutant is emitted at a low level, the maximum glc will occur upstream of the hill, so that the effect of

*On assignment from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

the hill will be negligible. If the source is tall enough, the maximum glc will occur far downstream of the hill, so that, again, the effect of the hill will be negligible. If the source is far enough upstream that the plume widths (σ_y and σ_z) are comparable to or larger than the hill dimensions, the effect of the hill will again be negligible. Hence a region or 'window' (Hunt *et al.*, 1979) exists such that pollutants emitted within that window will result in 'excessive' ground-level concentrations.

Recent fluid modeling studies (Snyder and Britter, 1987; Snyder, 1983; Castro and Snyder, 1982; Khurshudy *et al.*, 1981) have indicated that large increases in concentration (factors as large as 15) can result from placement of sources near terrain, but systematic studies to establish values and 'windows' of excess concentration have not been done. The purpose of this study was to determine to what extent terrain features might influence maximum ground-level concentrations, i.e. to establish values and 'windows' of excessive concentrations for typical hill shapes that might be found in the real world. Two hill shapes were chosen to represent two relative extremes of realistic hill shapes. The model hills, one axisymmetric and the other two-dimensional, represent idealizations of typical hills in shape and slope, so that the results of the study should be rather broadly applicable. Detailed measurements of the flow-field structure over the two hills are presented and plume behavior is described in terms of this structure.

The results are presented in terms of terrain amplification factors (TAFs), defined as the ratios of the maximum glcs in the presence of the hills to the maximum glcs in the absence of the hills (in flat terrain). Note that this definition does not involve the location of the maximum glcs; the maxima will generally occur at very different distances downstream from the source in the two situations (with and without terrain), but it is the value of the maxima which are being compared, wherever they occur. Note also that the 'excess concentration' is easily obtained from the TAF; they differ by the additive factor of unity, i.e. a 'zero' excess concentration, for example, is represented by a TAF of 1.0, and a 40% excess concentration by a TAF of 1.4.

The 'window' concept allows the specification of a region or area (say, in a vertical plane) such that sources placed inside the window would result in TAFs exceeding some specified value. Once an acceptable excess concentration or TAF is decided upon, it is a simple matter to trace the window on the TAF contour map as the area to be avoided. Conversely, from such maps, the likely maximum glc for a potential site and stack height can be estimated. The use of terrain amplification factors simplifies the application of these data to full-scale situations. The expected maximum glc in the absence of the obstacle is calculated (from mathematical models or standard curves), then the concentration in the presence of the obstacle is simply the product of this quantity and the TAF.

2. EXPERIMENTAL PROCEDURES AND INSTRUMENTATION

2.1. Wind tunnel

The experiments performed in this study were conducted in the meteorological wind tunnel of the U.S. Environmental Protection Agency's Fluid Modeling Facility. It is a low-speed, open-return wind tunnel with a test section 2.1 m high, 3.7 m wide and 18.3 m long. Detailed features and operational characteristics of the wind tunnel are described by Snyder (1979).

Simulation of atmospheric flow near the surface of the earth requires that the atmospheric boundary layer be properly modeled. The technique of Counihan (1969) was used to produce a deep simulated atmospheric boundary layer which developed very slowly after an initial rapid development. A combination of castellated fence, elliptic-wedge vortex generators, and surface roughness elements (commercially available Sanspray™ gravel-coated panels with an average grain size of approximately 3 mm) produced a near-equilibrium boundary layer with a nominal depth (δ) of 1 m. A scale ratio of 1250:1 was chosen to provide an equivalent full-scale boundary-layer depth of 1250 m.

2.2. Models

The axisymmetric hill was an idealized version of Cinder Cone Butte (Lavery *et al.*, 1982), an isolated, nearly axisymmetric hill located in southwestern Idaho. The model was 155 mm in height, 1550 mm in diameter, and had the shape of a fourth order polynomial:

$$f(r) = \frac{h+c}{1+\left(\frac{r}{L}\right)^4} - c,$$

where r is the radial distance from the hill center; $h = 155$ mm, $L = 388$ mm and $c = 10$ mm for $r \leq 775$ mm; and $f(r) = 0$ for $r > 775$ mm. The top of the model hill was a relatively flat plateau about 400 mm in diameter, while the sides sloped gradually to the surface with no discontinuities. The maximum slope was 24° .

The two-dimensional ridge was identical in shape and construction to "Hill 5" as described by Khurshudy *et al.* (1981), except that it was covered with gravel of a smaller size. The height of the model was 118 mm, its chord was 1180 mm, and its maximum slope was 16° . The shape is described by the following parametric equations:

if $|\xi| \leq a$, then

$$x = \frac{1}{2} \xi \left(1 + \frac{a^2}{\xi^2 + m^2(a^2 - \xi^2)} \right), \text{ and}$$

$$z = \frac{1}{2} m \sqrt{a^2 - \xi^2} \left(1 - \frac{a^2}{\xi^2 + m^2(a^2 - \xi^2)} \right),$$

where $m = 1.22$, $a = 590$ mm and ξ is an arbitrary parameter.

Cross-sections of both models can be seen in the accompanying figures (note that the vertical scale has been exaggerated by a factor of 3 for clarity). Both model hills were coated with fine gravel of the same size as that used for the surrounding flat-terrain roughness. This had the effect of blending the models smoothly into the surrounding terrain and maintaining an aerodynamically rough surface.

2.3. Velocity measurements

Measurements of mean velocity, longitudinal and vertical components of turbulence intensity and Reynolds stress were made using hot-wire anemometers with x-array sensors. The sensors were calibrated in the free-stream flow using a Pitot tube and capacitance manometer as a reference. A minicomputer system was used to digitize the anemometer output voltages, convert the digitized voltages to velocities and compute flow statistics. Corrections were applied to account for the effects of ambient temperature drift (Bearman, 1971) and finite-length sensor yaw response (Lawson and Britter, 1983). All measurements were carried out at a free-stream wind speed of 4 m s^{-1} .

Supplementary measurements were made on the downstream side of the axisymmetric hill using a dual Pitot tube. The sensor consisted of two small total head tubes soldered back-to-back and connected to a differential pressure sensor. The output from the pressure sensor changed sign as the velocity changed direction, enabling location of the point of zero mean velocity and, hence, estimates of the size of the separated wake and locations of the separation and reattachment points.

2.4. Concentration measurements

A hydrocarbon tracer technique was used to measure ground-level concentrations downwind of the source. The HC tracer used was ethane (C_2H_6), which has a molecular weight very near that of air, so that the plume was neutrally buoyant. The tracer was released through a hollow, perforated plastic ball 10 mm in diameter. This type of source allows for injection of a suitable quantity of tracer gas while at the same time minimizes the effluent momentum in any preferred direction; it simulates a point source and avoids any plume rise. Samples were withdrawn through sampling ports mounted on the surface of the model and on the tunnel floor. Port-to-port spacing was 150 mm which determined the spatial resolution with which the maximum ground-level concentration was determined. The samples were routed to flame ionization detectors (FIDs) which produced output voltages linearly related to concentration. The FIDs were calibrated using 'zero' air and a certified ethane 'span' gas. Separate tests prior to conducting measurements showed the FIDs to respond linearly over four decades of ethane concentration. The output voltage from

the FIDs was sampled by the minicomputer system at a rate of one sample s^{-1} over an averaging time of 120 s, which yielded reasonably stable values of mean concentration. Since the response time of the analyzers was on the order of 1/2 s, no attempts were made to measure concentration fluctuations. Concentrations are converted to nondimensional form,

$$\chi = \frac{CU_\infty h^2}{Q},$$

where C is the volume concentration, U_∞ is the free-stream wind speed, h is the hill height and Q is the ethane volumetric flow rate ($30.40 \text{ cm}^3 \text{ min}^{-1}$).

3. BOUNDARY LAYER CHARACTERIZATION IN FLAT TERRAIN

The boundary-layer structure was characterized through measurements of mean velocity, turbulence structure and dispersive ability. This characterization was carried out in the absence of any model and at the same free-stream wind speed as used with the models in place (4 m s^{-1}). The wind-tunnel ceiling was adjusted to compensate for the growth of the boundary layer; measurements showed the variation of free-stream wind speed along the length of the test section to be no more than $\pm 2\%$.

3.1. Velocity

Figures 1a and 1b show measurements of mean velocity (U/U_∞) and turbulence intensity (σ_u/U and σ_w/U , where σ is the root-mean-square of the velocity fluctuations) taken at 6, 10 and 15 m downstream from the start of the roughness panels. Very little change in the structure of the boundary layer occurred beyond 6 m. The model hills were located at 6.5 m (and later at 9.1 m); hence, the effect of changes in the boundary layer structure are expected to be minimal. A roughness length of approximately 0.1 mm ($\approx 12.5 \text{ cm}$ full scale) and normalized friction velocity (u_*^*/U_∞) of 0.045 were obtained by fitting the lower portion of the mean velocity profile to a log-law form. A 0.12 power-law profile is shown for comparison in Fig. 1a. According to Irwin (1979), this is representative of a neutral boundary layer with rural upstream terrain. Figure 1c shows the measured shear-stress ($-\overline{u'w'}$) distribution normalized by the square of the friction velocity derived from the log-law fit.

3.2. Concentration

Surface concentration of tracer material was measured as a function of the distance downstream of the source for several different source heights (Fig. 2). These profiles served as the flat terrain or reference data for later evaluation of terrain amplification factors. In Fig. 3, the maximum ground-level concentration is plotted as a function of stack height. The concentration decreases as the square of the stack

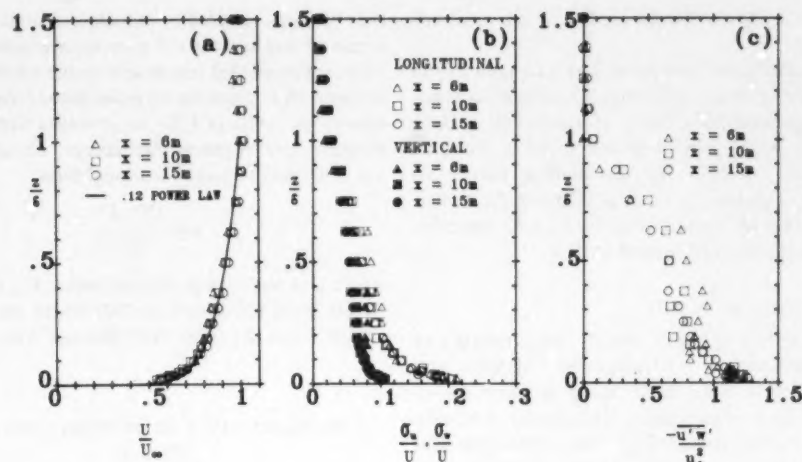


Fig. 1. Mean velocity, longitudinal and vertical turbulence intensity and Reynolds stress measured in the simulated atmospheric boundary layer with a 6 m, 10 m and 15 m upstream fetch.

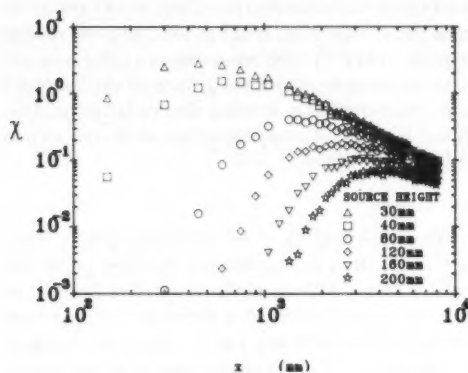


Fig. 2. Centerline ground-level profiles of tracer concentration in flat terrain as a function of downstream distance from the source for various source heights. (Non-dimensionalized using $h = 113$ m in all cases.)

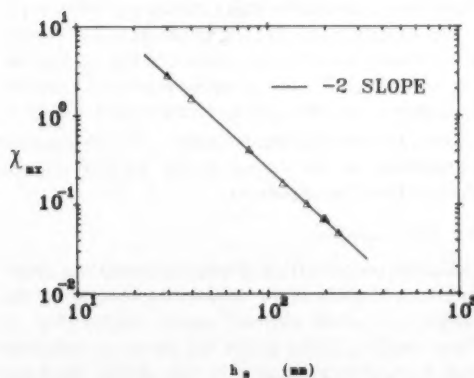


Fig. 3. Maximum ground-level concentration in flat terrain as a function of source height. (Non-dimensionalized as in Fig. 2.)

height and is consistent with that expected from a Gaussian plume model. The location of the maximum ground-level concentration was found to vary as the 1.2 power of the stack height, consistent with the results of Khurshudyan *et al.* (1981).

A comparison was made between measured dispersion characteristics in the wind tunnel and those estimated using Pasquill-Gifford stability categories C and D (Turner, 1970), as shown in Fig. 4. A scale factor of 1:1250 was used. Near the source, the dispersion was most closely approximated by stability class C, while farther downstream the dispersion was more typical of stability category D. Also shown is a comparison with the dispersion scheme suggested by Hosker (1974), Gifford (1975) and Smith (1973) for stability category D and a 10 cm roughness length. This scheme uses a distance-dependent roughness-

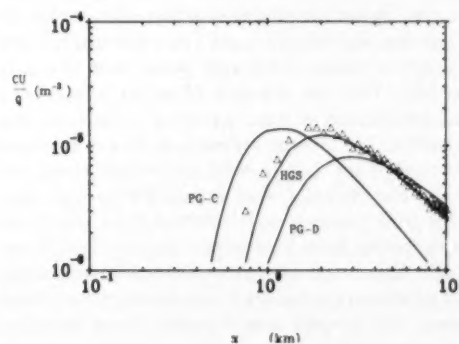


Fig. 4. Measured dispersion characteristics in the wind tunnel compared with dispersion estimates using Pasquill-Gifford stability classes C and D, and Hosker, Gifford and Smith's scheme for stability class D and a 10 cm roughness length. Assumed scale ratio is 1250:1. x is measured from the source.

correction-factor technique and matches the data much better than the Pasquill-Gifford stability classification scheme for either C or D stability.

region was observed for the axisymmetric hill, but no clearly defined recirculating zone was seen downstream of the two-dimensional ridge.

4. FLOW VISUALIZATION

Some flow visualization experiments were conducted with each hill prior to making quantitative concentration measurements. These qualitative evaluations of the dispersion near the hills were used as a guide in selecting appropriate locations for the tracer source, and in determining whether the flow was separating on the downstream side of the hills. A thin separated

5. RESULTS

Figures 5-7 show the longitudinal component of mean velocity, longitudinal component of turbulence intensity and vertical component of turbulence intensity, respectively, for the axisymmetric hill and the two-dimensional ridge. Seventeen vertical profiles of these quantities, spanning the range from 15 hill heights upstream to 15 hill heights downstream, were

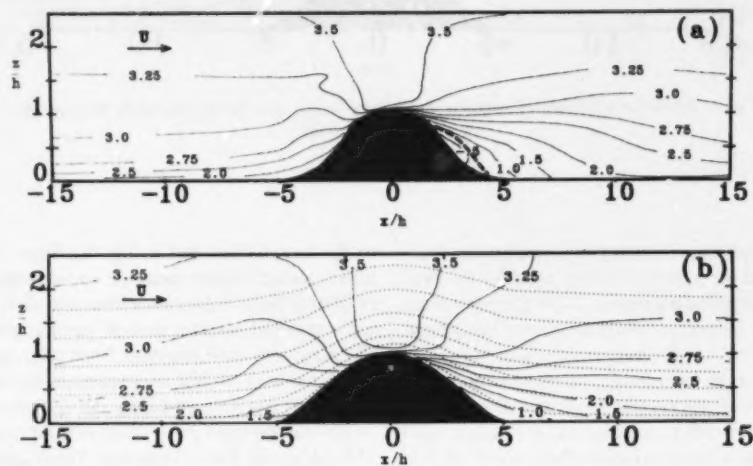


Fig. 5. Isotachs (in ms^{-1}) over (a) axisymmetric hill and (b) two-dimensional ridge. Streamlines over the two-dimensional ridge are indicated by dotted lines. Note that the hill shape is exaggerated in the vertical direction by a factor of 3.

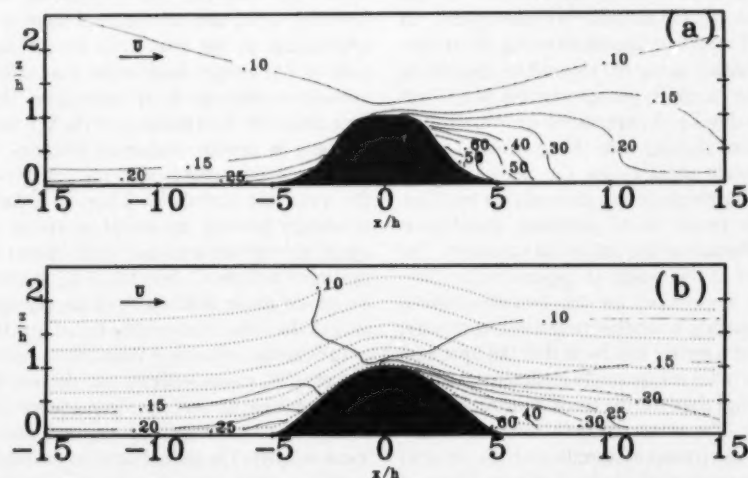


Fig. 6. Longitudinal component of turbulence intensity (σ_u/U) over (a) axisymmetric hill and (b) two-dimensional ridge.

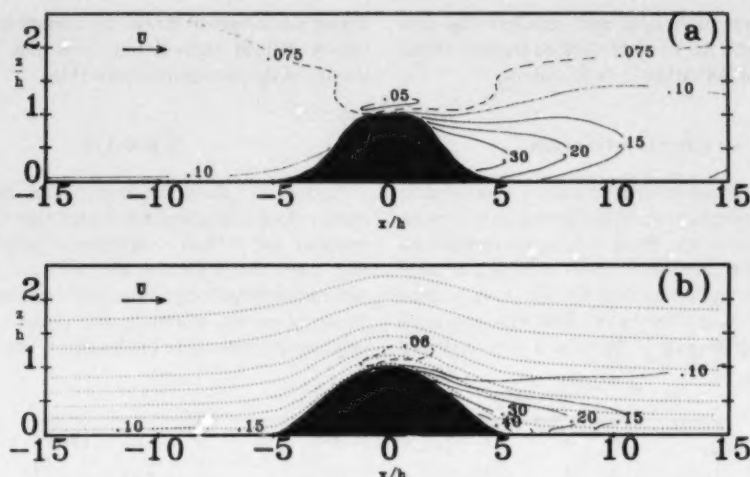


Fig. 7. Vertical component of turbulence intensity (σ_w/U) over (a) axisymmetric hill and (b) two-dimensional ridge.

used to construct the contour plots. Streamlines were calculated from the mean velocity profiles for the two-dimensional ridge and are shown as the dashed lines in the figures. Turbulence intensity measurements shown are with respect to the major axes and were not measured along the streamlines. Measurements in the near-wakes of the hills should be used with caution as the intensities are sufficiently high to cause substantial errors in hot-wire measurements (Tutu and Chevray, 1975), and flow reversals near the separated region cannot be detected. Dual-Pitot-tube measurements were used to delineate the locus of zero mean velocity for the axisymmetric hill.

In Figs 5a and b, the most apparent effect of the hills on the mean velocity is a substantial speed-up over the top of the hill. This is best illustrated in Fig. 5b where a fluid parcel released along the streamline originating upstream at, for example, one-quarter hill height will gradually slow down as it approaches the hill, encounter a pronounced slowing near the upstream base of the hill, accelerate rapidly over the top of the hill, undergo rapid deceleration as it descends the lee slope, then gradually return to its upstream speed as it escapes the influence of the hill far downstream. The speed-up factor at this height is approximately 30% (following the streamline) for the two-dimensional ridge and, assuming a similar trajectory, somewhat less for the axisymmetric hill. Note that the upstream influence of the hill is substantially greater for the two-dimensional ridge than for the three-dimensional axisymmetric hill. The wakes of both hills show substantially reduced transport speeds. For the axisymmetric hill, separation and reverse flow were observed on the downstream side. The locus of zero mean velocity as measured with the dual Pitot tube is shown

as the bold dashed line in Fig. 5a. Since the hot-wire anemometer cannot measure vector wind speeds in reversing flows, velocities within and near this region are somewhat suspect; indeed, comparison of velocities measured with the dual Pitot tube against those measured with the hot-wire anemometer indicate that the hot-wire is overestimating the velocity by as much as 60% along the 1 m s^{-1} contour and by as much as 25% along the 2 m s^{-1} contour. These inherent errors in the measurement technique should be kept in mind when examining the near-wake measurements.

Figures 6 and 7 show the longitudinal and vertical components of turbulence intensity over the axisymmetric hill and the two-dimensional ridge. Again referring to the two-dimensional ridge, a fluid parcel originating on the streamline at, for example, one quarter hill height encounters gradually increasing turbulence intensity as it approaches the upstream base of the hill. As it passes over the hill, the turbulence intensity is rapidly decreased followed by a rapid increase as the wake is encountered. Downstream of the wake, the turbulence intensity begins a gradual relaxation towards the initial upstream value. Once again, the two-dimensional ridge shows the greatest upstream influence while the axisymmetric hill, with its greater slope, exhibits considerably more disturbance in the wake. It should be noted that the variation in turbulence intensity is primarily a reflection of the variation in mean velocity, i.e. the variation in the absolute value of the root-mean-square (rms) velocity fluctuations is considerably less than the variation in mean velocity. The spatial variation of the rms components, σ_w and σ_u , were found to be consistent with the two-layer model proposed by Hunt (1980) and the recent observations and calculations of Zeman and

Jensen (1987). Both the magnitude of the rms fluctuations and the ratio σ_w/σ_u were found to be essentially identical on the upstream side and top of both hills.

Figure 8 illustrates some typical comparisons between the flat-terrain ground-level concentration measurements and those measured with the hills in place. In Fig. 8a, centerline ground-level concentration profiles for the axisymmetric hill are plotted for sources located at 4 and 8.3 hill heights downstream of the hill and 0.77 hill heights above the surface. The peak nondimensional concentration at these locations is seen to be 1.28 and 0.46, respectively, whereas the flat-terrain data show a peak value of 0.295. The terrain amplification factors (TAFs) are thus 4.34 and 1.56, respectively, for these two source locations. Similarly, in Fig. 8b, ground-level concentration profiles in the presence of the two-dimensional ridge with sources at 5 and 10.9 hill heights downstream and 1.02 hill heights above the surface show peak concentrations of 0.572 and 0.285. The flat-terrain data show a peak value of 0.176; hence, the TAFs are 3.25 and 1.62, respectively. Note that different hill heights were used in nondimensionalizing the concentration in the two cases (but, because the TAFs are ratios of concentrations, the values indicated are independent of the hill height used in normalizing the concentrations).

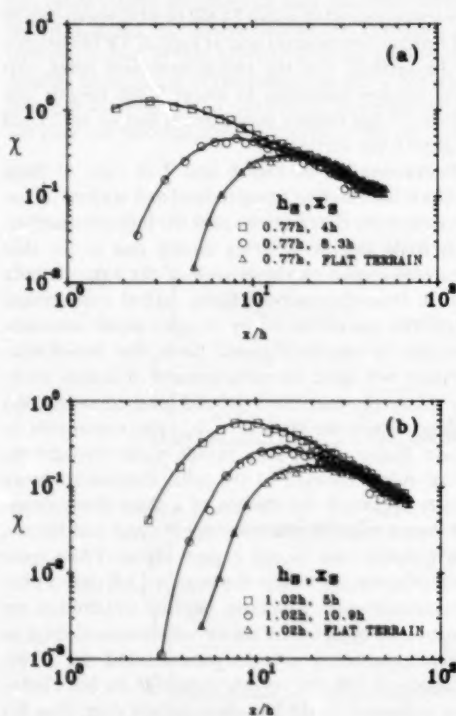


Fig. 8. Comparison of flat-terrain ground-level concentration measurements with those in the presence of (a) axisymmetric hill and (b) two-dimensional ridge. Source locations indicated are downwind of the hills.

Similar procedures were applied to an array of source locations, producing the TAF values shown in Fig. 9. TAFs upstream of the axisymmetric hill were obtained from a previous study by Thompson and Snyder (1985). Experimental conditions were essentially identical to those used in the current study and the data appear to be consistent with the current results. For both hills, the greatest TAFs occurred with the source on the downstream side; maximum values of 5.6 were observed for the axisymmetric hill and 6.8 for the two-dimensional ridge. With the source on the upstream side, the axisymmetric hill exhibited somewhat higher TAFs than did the ridge; the peak values were 3.6 and 1.8, respectively. The maximum TAF value for the axisymmetric hill occurred with the source on the downstream side of the hill and at a height of about $0.5h$. In Fig. 5, this location is seen to correspond closely to the boundary of the separated region. This is consistent with the results of Castro and Snyder (1982), who concluded that the largest amplification factors for three-dimensional hills occurred when the effluent was emitted near the separation-reattachment streamline, so that the plume impacted directly on the ground. For the two-dimensional ridge, the largest TAF was found to occur near the downstream base of the hill. Examination of Figs 5, 6 and 7 shows this to be a region where streamlines are descending toward the surface, the turbulence intensity is considerably enhanced and the average transport speed quite low. This combination of circumstances results in the plume being quickly diffused to the surface, leading to a high glc and, hence, a high TAF.

Khurshudyan *et al.* (1981), using a hill similar in shape and slope but with larger surface roughness ($z_0 = 0.16$ mm vs $z_0 = 0.10$ mm), found substantially higher TAFs at the downstream base of the hill. Their data show TAFs of 15.0 at $z/h = 0.25$, 8.1 at $z/h = 0.5$, 5.6 at $z/h = 1.0$, and 2.9 at $z/h = 1.5$. The corresponding values in the current study were 6.8, 6.8, 5.6 and 2.1, respectively. The discrepancy between these data and the present study require explanation. First, even though the model hill of Khurshudyan *et al.* was rougher, this is not expected to result in large changes in the TAFs. For a continuous release, the glc which results when a plume encounters the surface is directly proportional to the source strength and inversely proportional to the transport speed and plume cross-sectional area, the latter generally being specified in terms of lateral and vertical plume spread, σ_y and σ_z . Additionally, the plume trajectory determines how far the plume must spread before reaching the surface. Data from Khurshudyan *et al.* show the mean velocity at $z/h = 0.25$ to be about 25% lower over the rough surface in the wake of the hill, while values of σ_w (and presumably σ_z) were nominally the same in both cases. Hence, any large differences in the TAF would have to be due to large differences in σ_y . Khurshudyan *et al.*, however, found that lateral plume widths were generally enhanced by the presence of the hills and should,

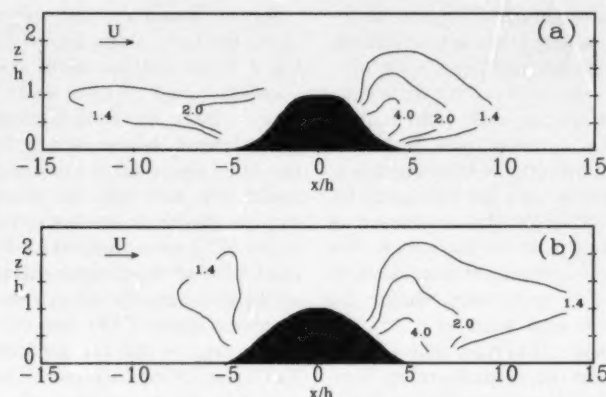


Fig. 9. Contours of constant terrain amplification factor over (a) axisymmetric hill and (b) two-dimensional ridge. The contours enclose 'windows' or regions where the combination of source height (z/h) and distance from the hill (x/h) are such that the maximum ground-level concentration resulting from these source locations exceeds that for flat terrain by at least the indicated contour value.

therefore, lead to decreased TAFs. Examination of the locations of the maximum glc in both cases showed them to be nearly the same; indeed, at $z/h = 0.25$, the maximum glc was found almost directly under the source. This implies that the plume trajectory was such that the plume was swept directly to the surface with very little mixing taking place. The result is that the concentration gradient is very high near the source and, hence, the 150 mm port spacing used in the current study (as opposed to the 10–20 mm resolution of Khurshudyan *et al.*) is probably inadequate to resolve the true maximum glc. At greater distances from the source, where the gradient of concentration is substantially weaker, the 150 mm port spacing is entirely adequate as seen in Fig. 8. Since the smoother surface (hence lower turbulence intensity) used in the current study should lead to even larger gradients of concentration, it is likely that the current data do not accurately reflect the true maximum glc near the downstream base of the hill and could, conceivably, mask even higher TAFs than those observed by Khurshudyan *et al.* As the distance from the downstream base increases, the TAFs become more consistent with those measured by Khurshudyan *et al.*; remaining differences are on the order of those to be expected from the differences in surface roughness. Comparison of TAFs near the upstream base and over the top of the hill also show reasonably good consistency between the two studies.

The distribution of terrain amplification factors has been illustrated in Fig. 9 by construction of contours of constant terrain amplification factor for TAF values of 1.4, 2.0 and 4.0. Note that these contours form 'windows' within which the maximum glc exceeds that which occurs in flat terrain by 40%, 100% and 300%, respectively. Differences between the TAF distribu-

tions for the axisymmetric hill and the two-dimensional ridge are most clearly seen in the vertical and longitudinal extent of the windows of 40% excess concentration (TAF of 1.4). For the axisymmetric hill, this region extended about 14 hill heights upstream, 10 hill heights downstream and as high as 1.8 hill heights in the vertical. For the two-dimensional ridge, this same window extended to about 8 hill heights upstream, 15 hill heights downstream and up to 2.2 hill heights in the vertical.

Reexamination of Figs 6 and 7 in view of these results is informative. Longitudinal and vertical turbulence intensity distributions near the hills are qualitatively quite similar, differing mainly due to the thin separated region on the lee side of the axisymmetric hill. In three-dimensional flows, lateral and vertical intensities are enhanced by roughly equal amounts, whereas, in two-dimensional flows, the two-dimensionality will limit the enhancement of lateral intensity. Since the maximum ground-level concentration depends upon the ratio of σ_z/σ_y , it is reasonable to expect higher TAFs downwind of the two-dimensional ridge. Upwind of the hills, streamlines more closely approach the surface of a three-dimensional hill than a two-dimensional ridge (Snyder and Britter, 1987); hence, one would expect higher TAFs from sources upwind of a three-dimensional hill than a two-dimensional ridge. Similarly, because streamlines are constrained to flow over the two-dimensional ridge as opposed to being able to pass around the three-dimensional hill, the vertical extent of the hill's influence is greater for the two-dimensional ridge than for the three-dimensional hill.

Application of the data in Fig. 9 is straightforward. Consider, for example, a source which is located 7 hill heights upstream of a nearly axisymmetric hill and

extends vertically to 0.5 hill heights. The intersection of $x/h = -7$ and $z/h = 0.5$ in Fig. 9a shows that the maximum ground-level concentration to be expected from such a source location would be on the order of twice that which would be observed for the same source in flat terrain. If, on the other hand, the hill were more nearly two-dimensional, then a similar application of Fig. 9b shows that the anticipated maximum ground-level concentration would only be on the order of 20% (TAF = 1.2) greater than that which would be expected in flat terrain. While precise interpolation of TAFs for hills intermediate in shape and slope to those examined in this study may be difficult, it is clear that some useful limits may be placed on the effects of hills with intermediate shapes and slopes.

Figure 10 shows the loci of source positions leading to the same locations of maximum ground-level concentration. These loci have been identified by marking them with the position of the maximum ground-level concentration (in hill heights) from the centers of the hills. Note that the 'undisturbed' or flat terrain loci (dotted lines) are simply parallel, diagonal lines. In the presence of the hills, these loci are distorted as shown by the solid lines. Whereas these diagrams may at first appear somewhat esoteric, they are not difficult to understand, and they are really quite utilitarian. For any given source position, we may plot that position on the diagram, then follow the contour to the ground; the intersection of that contour with the ground is, of course, the location of the maximum glc. Conversely, from a knowledge of the location of the maximum glc, we may use the diagram to determine the line along

which the source was positioned. For both hills there are three distinct regions: (1) a region near the upstream surface where a plume released from the source will result in a maximum glc upstream of the hill, (2) a region upstream of the hill and above the surface where the plume will essentially graze the top of the hill and result in a maximum glc on the hill top, and (3) all other source locations, where the plume goes over the hill and results in a maximum glc on the downstream side. As the distance (both vertical and longitudinal) from the source to the hills increases, these contours gradually relax to their undisturbed or flat-terrain values.

Note that, for the three-dimensional hill (Fig. 10a), if an upwind source is above the hill top, the position of the maximum glc will be on the lee side of the hill. For the two-dimensional hill (Fig. 10b), an upwind source $> 3/4$ of the hill height would result in a lee-side location of the maximum glc. Only very narrow bands of source positions exist that result in locations of maximum glcs on the hill top.

6. CONCLUSIONS AND APPLICATIONS

These experiments have shown that, even for sources located significant distances from terrain obstacles (10–15 hill heights), significant increases in maximum glc can occur over and above those which would occur in the absence of the hills. Using the same scale factor as used for the comparison with Pasquill-Gifford dispersion curves (1:1250), for example, the axisymmetric hill would scale to about 200 m in height, and

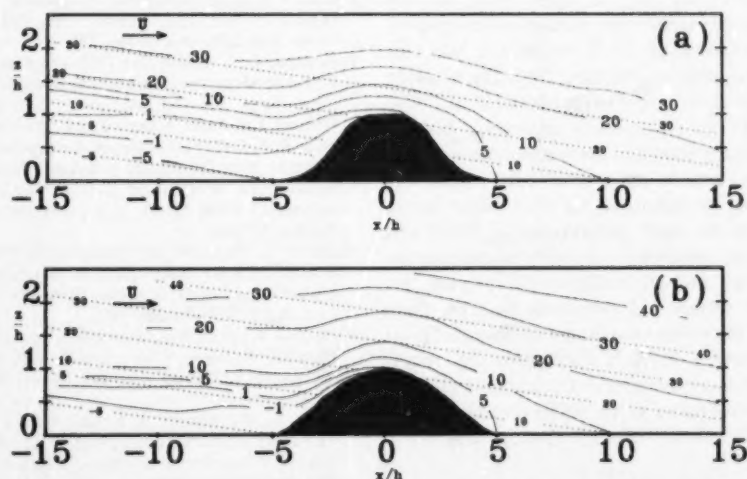


Fig. 10. Distance in hill heights from the hill center to the location of maximum ground-level concentration for (a) axisymmetric hill and (b) two-dimensional ridge. Flat-terrain values are indicated by dotted lines.

the ridge would scale to about 150 m. These hills would then account for significant excess concentrations for sources located approximately 2.0–2.5 km upstream and downstream, respectively. These data can be applied, with some restrictions, for scale ratios other than that considered in this study. So long as the ratio of hill height to boundary layer depth (0.12–0.16 in this study) and the hill slope remain similar to these 'generic' hills, the basic flow structure will be similar and, hence, the terrain amplification factors can be expected to be similar. Thus, for hills which are, for example, 1 km high, similar TAFs would be expected, but the extent of the region of 40% excess concentration would be on the order of 10–12 km upstream and downstream. Khurshudyan *et al.* (1981) showed that, for two-dimensional hills, increased slope leads to larger terrain amplification factors for upwind sources, consistent with increasing convergence of the streamlines. For downwind sources however, the greatest TAF was found to occur at a slope such that lee-side separation was incipient.

Some caveats should be noted before attempting to apply this information directly to real-world situations. In the wind tunnel, the mean wind direction remains absolutely steady, whereas, in the atmosphere, lateral fluctuations in wind direction or 'meandering' are more common than not. Average concentrations measured in the wind tunnel are thus more representative of the relatively short (10–30 min) periods in the atmosphere during which the wind tends to be reasonably steady. At other times, such 'meandering' tends to spread a diffusing plume laterally, hence, lowering the average concentration at any particular downstream location. These lateral fluctuations are frequently enhanced by terrain features so that, by comparison, the wind tunnel results are expected to produce slight overestimates of the peak concentrations. On the other hand, the hills considered in this study were selected to be representative of a broad range of hill shapes. For hills with greater slope (Castro and Snyder, 1982; Khurshudyan *et al.*, 1981) or more salient edges (Huber *et al.*, 1976), upstream vortices and lee-side separation may be induced or greatly enhanced. Both phenomena tend to bring plumes closer to the ground, hence, increasing maximum glcs. In such cases, the wind tunnel results may prove to be slight underestimates. While this study has been concerned only with neutral atmospheric stability, strongly stable conditions may also lead to high surface concentrations through direct impaction of the plume onto the terrain feature. Direct impaction under a strongly stable flow regime will generally lead to a maximum surface concentration on the order of that found at the plume centerline in the absence of the terrain obstacle (Snyder and Hunt, 1984).

Comparison of the present results with other wind tunnel studies is informative. Snyder and Lawson (1985), in a study of good-engineering-practice (GEP) stack height in complex terrain, applied the results of

the current study to the determination of an appropriate stack height for a particular power plant. The plant was located some 600 m downstream of a 190 m high, three-dimensional hill, and all the terrain within 6 km upstream and downstream and 3.5 km either side of the plant was modeled in detail. Direct application of the results of the current study indicated that the required stack height based on 40% excess concentration (TAF of 1.4) would be about 1.7 times the hill height, or 325 m. A rather laborious evaluation of GEP stack height for the specific terrain arrived at a value of 326 m. The nearly perfect agreement is certainly fortuitous, but it does indicate that studies of such 'generic' terrain features can provide suitable guidance for initial estimates of pollutant concentrations in complex terrain.

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